

# Photon science at FLASH during the last user campaign 2008/9



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FLASH-Seminar  
13. October 2009

# Summary of FLASH operation

**Wavelength range (fundamental):**

**6.8 - 47 nm**

**Spectral width (FWHM):**

**0.5 - 1 %**

**Pulse energy:**

**up to 100  $\mu$ J (average),  
200  $\mu$ J (peak)**

**Pulse duration (FWHM):**

**10 - 50 fs**

**Peak power (fundamental):**

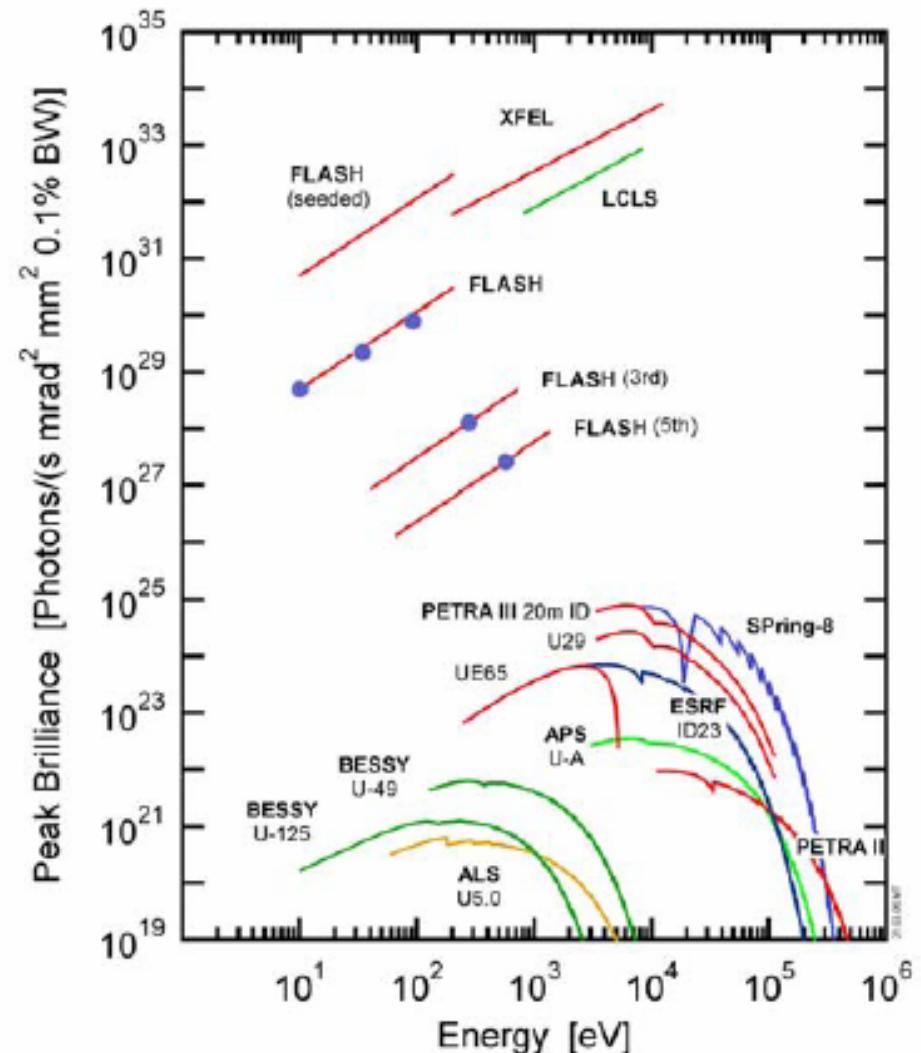
**1-5 GW**

**Average power (fundamental):**

**up to 0.1 W (up to 3000 pulses / sec)**

**Peak brilliance:**

**up to  $5 \times 10^{29}$**



**peak brilliance**

# From photons and atoms

atomic timescale:  
fs ... ps ... ns ...  $\mu$ s

> sunshine on a nice day

- 0.1 W/cm<sup>2</sup> → 1 Photon per atom / sec ( $10^{-14}$  Ph / 10 fs)

> sunshine focussed with a lens ( paper starts burning)

- $\sim 10^6$  W/cm<sup>2</sup> →  $10^7$  Photons per atom / sec ( $10^{-7}$  Ph / 10 fs)

> focussed optical TW laser ( ~ since 1990)

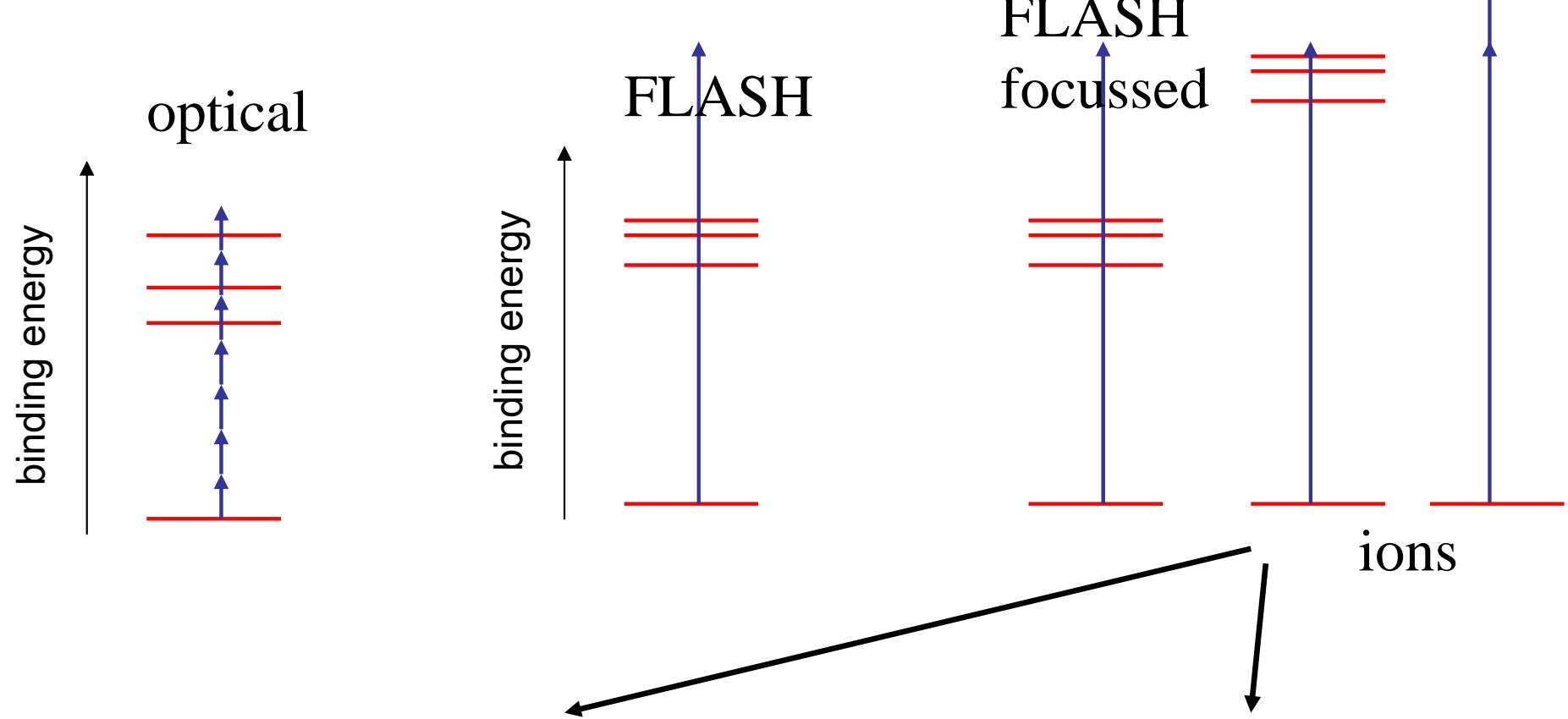
- $\sim 10^{18}$  W/cm<sup>2</sup> →  $10^{19}$  Photons per atom / sec ( $10^5$  Ph / 10 fs)

> focussed FLASH (13 nm)

- $\sim 10^{17}$  W/cm<sup>2</sup> →  $10^{16}$  Photons per atom / sec ( $10^2$  Ph / 10 fs)



# From photons and atoms



## Explore nature at its extremes

- test theories at limits
- „understand“ processes better
- FEL pulse interaction part of the experiment

## Apply the radiation

- imaging
- „detect“ interactions  
(solid state, plasma...)

# Few numbers on the beamtime

Beamtime 2008 – April 2009 (relative numbers for summer 2009 are similar)

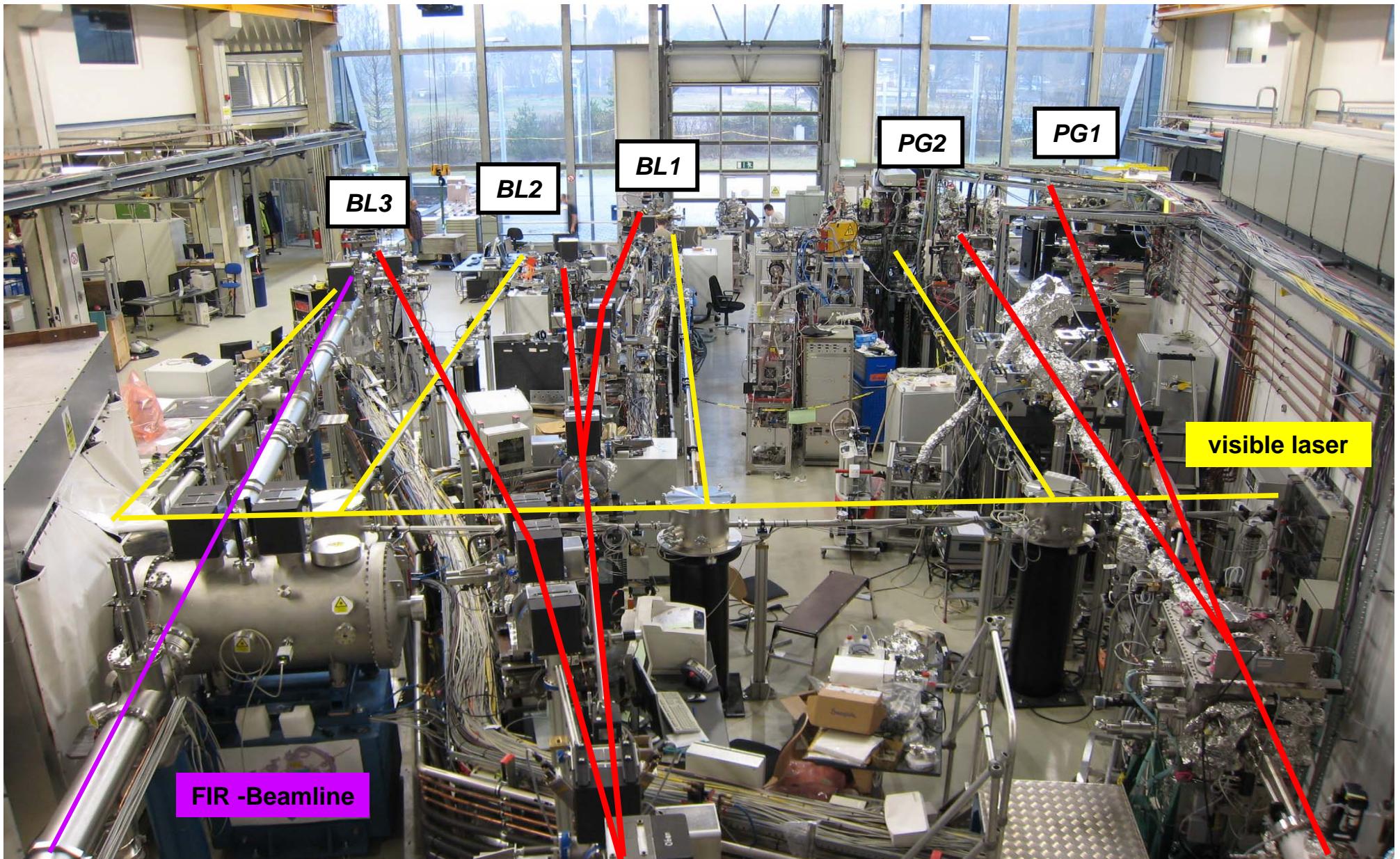
Topic	Groups	Shifts
Interaction with atoms, molecules and clusters	8	120
Imaging	2	44
Plasma physics	4	46
Solid state physics	3	42
Technical experiments (pulse duration...)	3	32

**40 % of the experiments requested the optical fs-laser**

# Research Highlights from FLASH



# FLASH Experimental Hall



## FLASH pulse duration

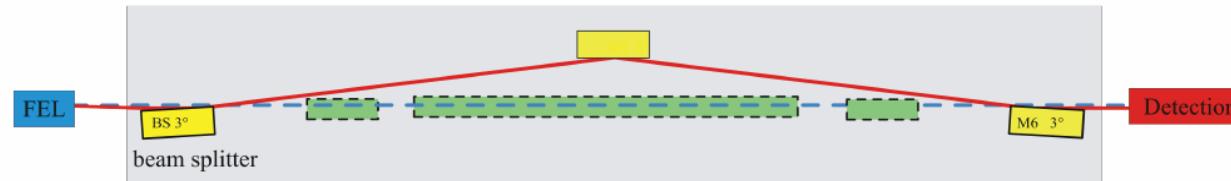
- Soft X-ray Autocorrelators (“Split & Delay Units”)
- FIR streaking



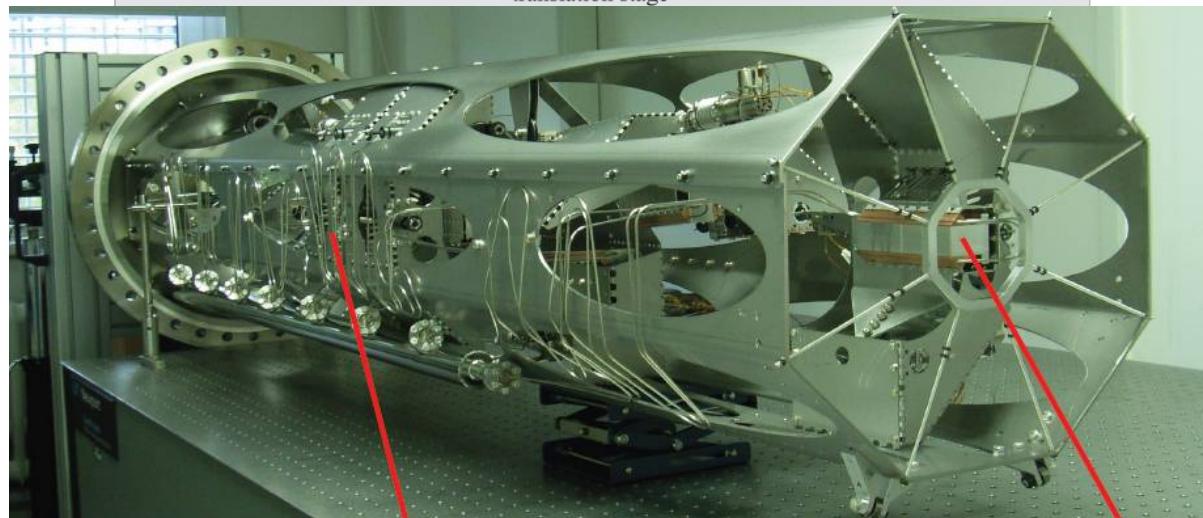
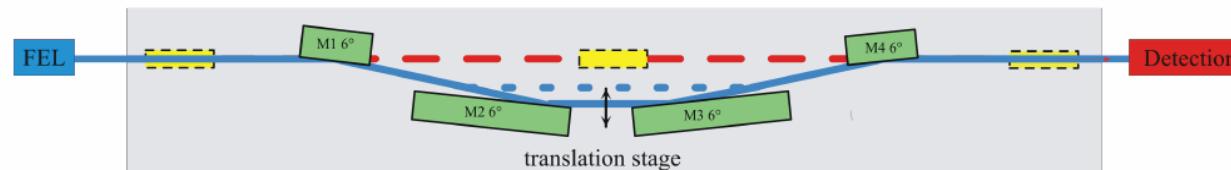
# Autocorrelator / Beam Split & Delay (1)

Uni Münster (H.Zacharias), BESSY, DESY

top view - fixed delay arm

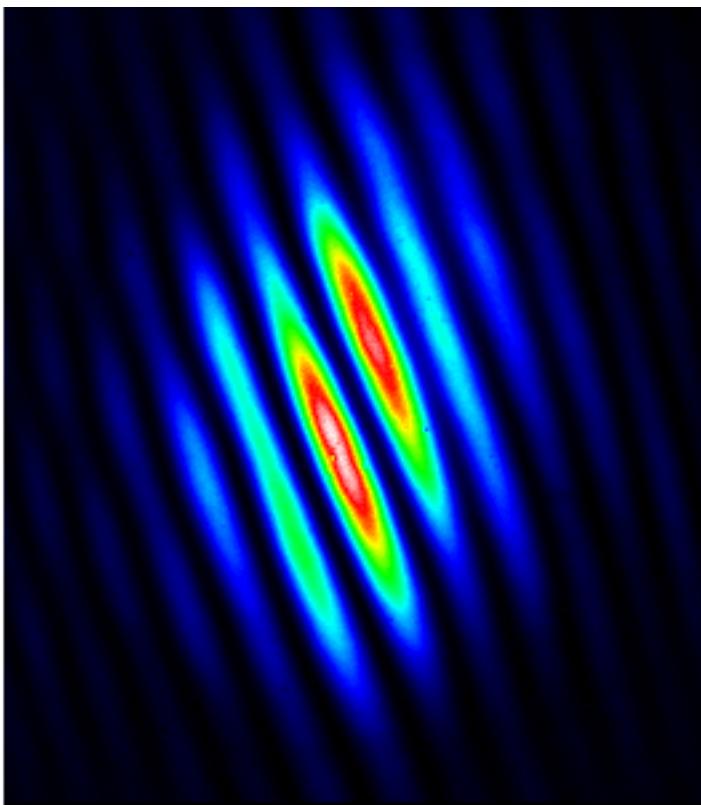


side view - variable delay arm

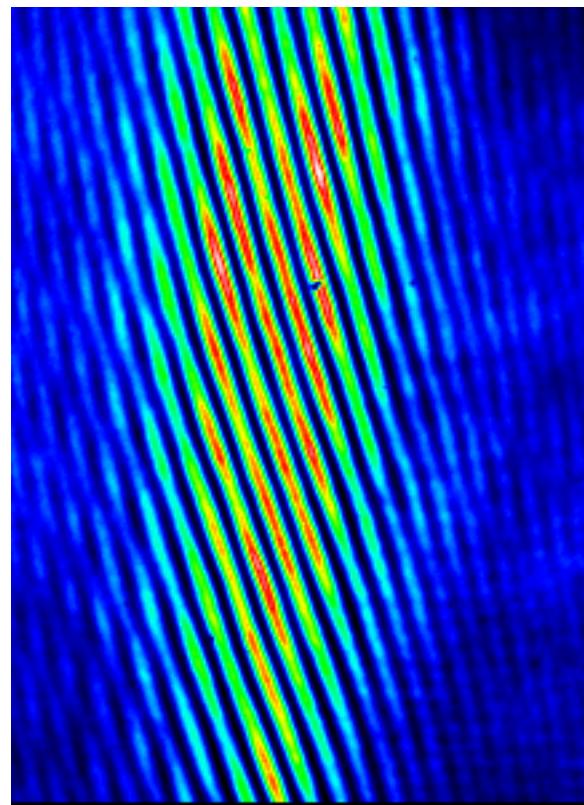


# Longitudinal coherence of FLASH pulses (1)

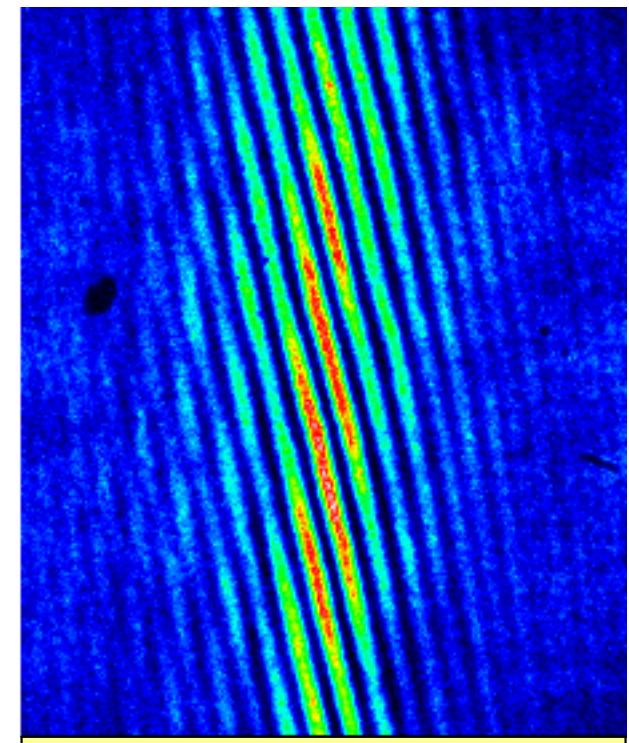
24 nm fundamental



8 nm fundamental



8 nm 3rd harmonic



Courtesy Björn Siemer

Coherence length at 8 nm: ~10 fs (~7 fs for 3rd harm.)  
Pulse duration at 24 nm: ~30 fs

Uni Münster (H. Zacharias), BESSY, DESY

# He<sup>2+</sup> autocorrelation measurements

Mitzner et al., PHYSICAL REVIEW A **80**, 025402 (2009)

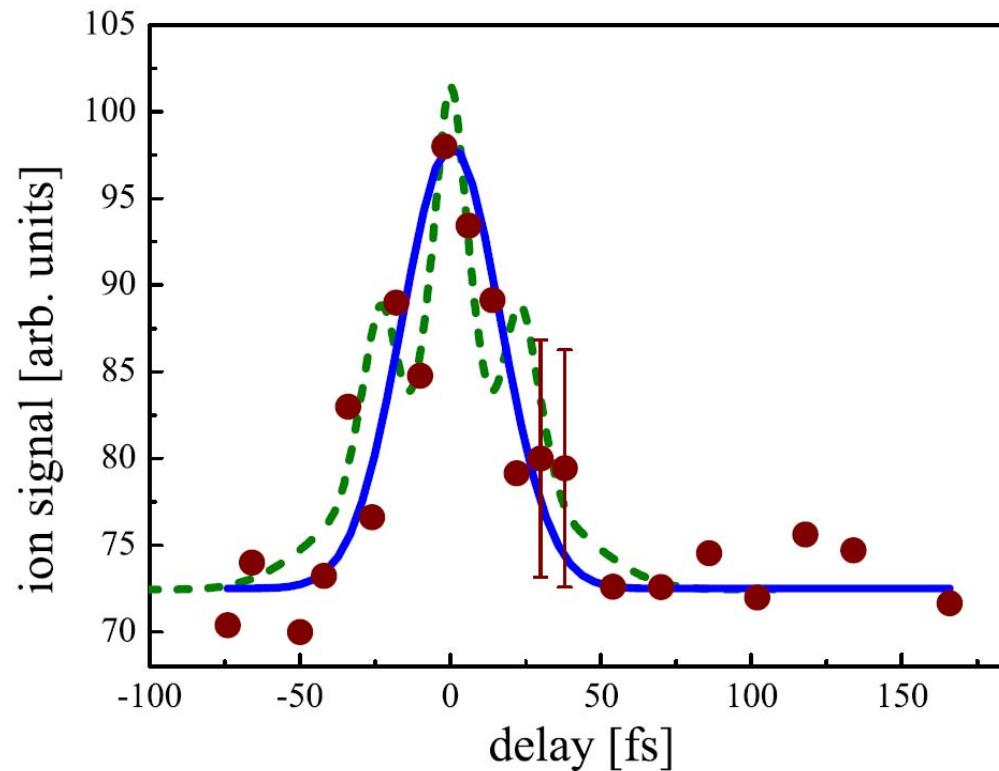
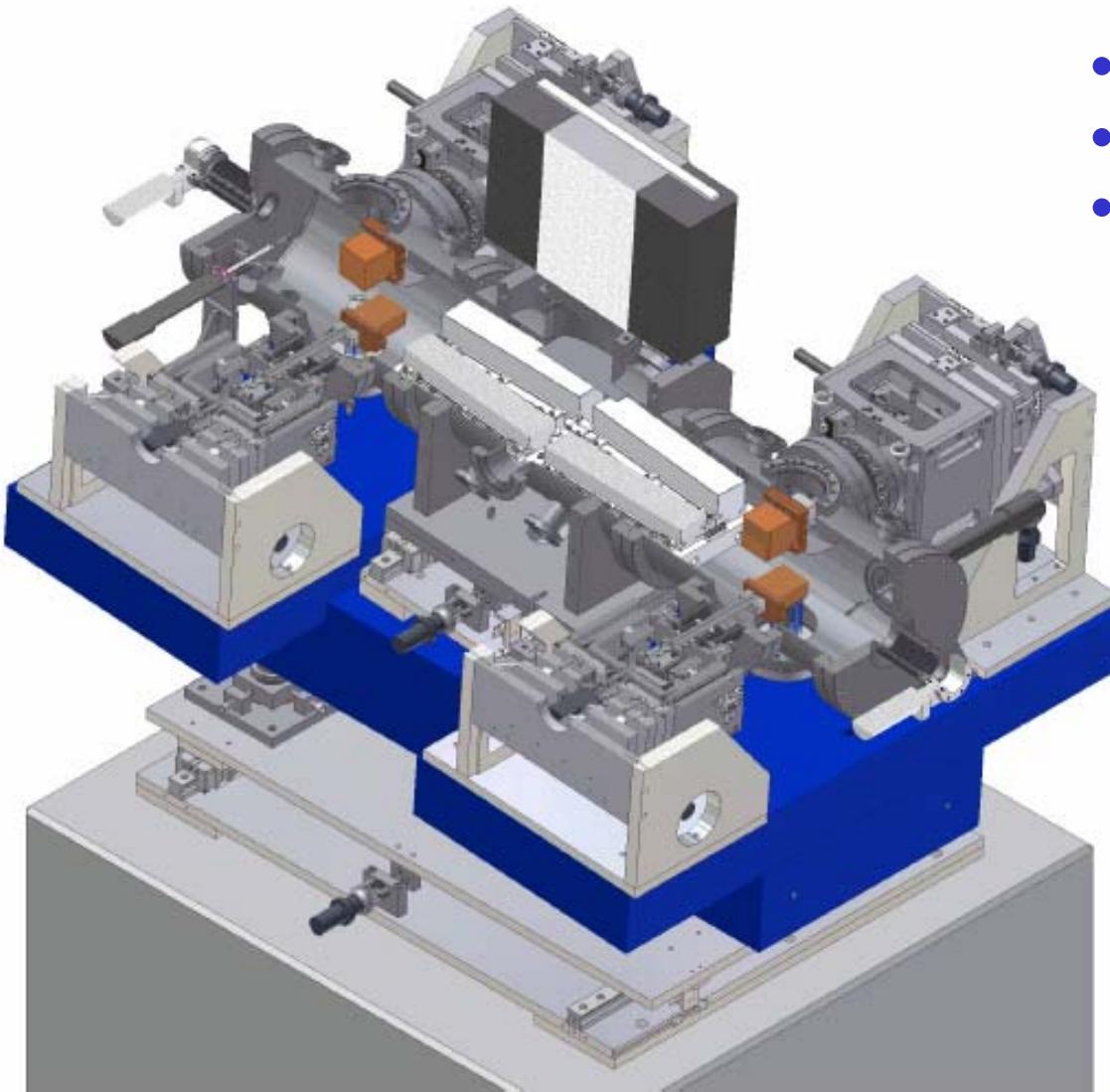


FIG. 1. (Color online) Time-resolved double ionization of He (dots). The solid line denotes a Gaussian function with 39 fs FWHM yielding a pulse duration of  $\tau_L = (29 \pm 5)$  fs, the dashed line represents a three-pulse structure with temporal separations of the maxima of 12 and 40 fs and an added chirp of  $50 \text{ fs}^2$  as inferred from Ref. [16].

# Autocorrelator / Beam Split & Delay (2)

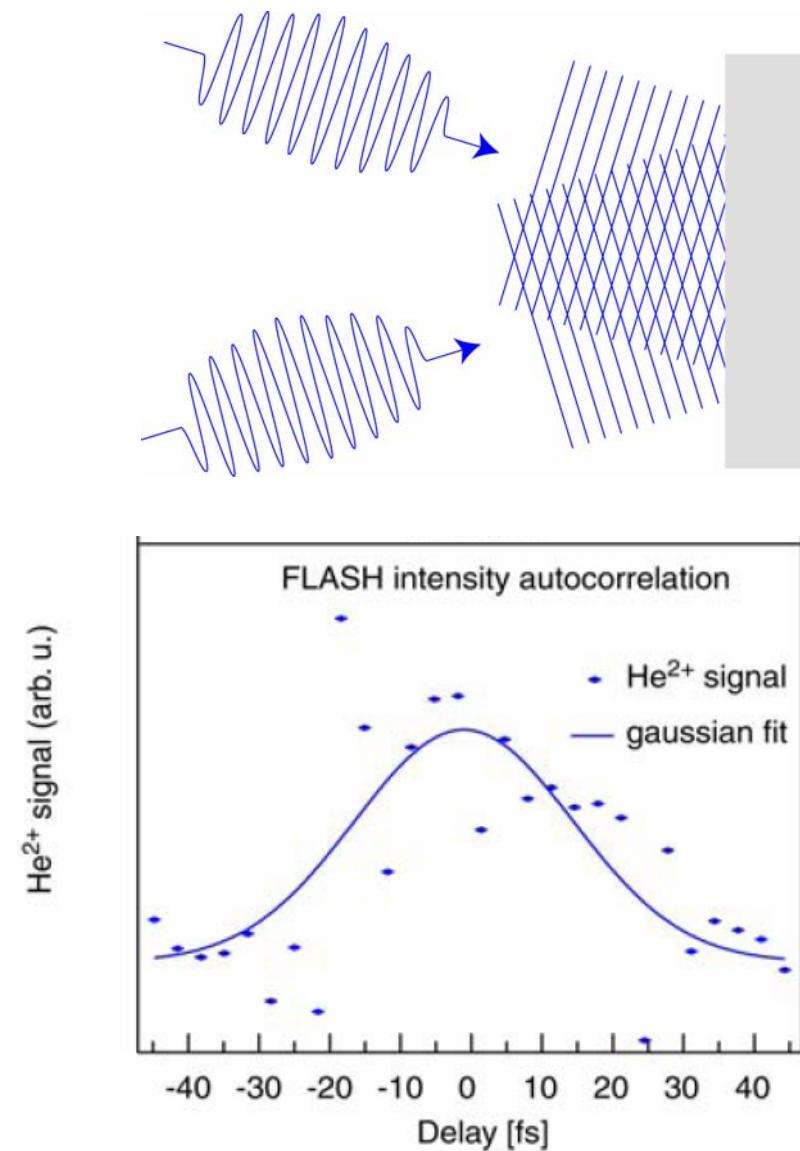
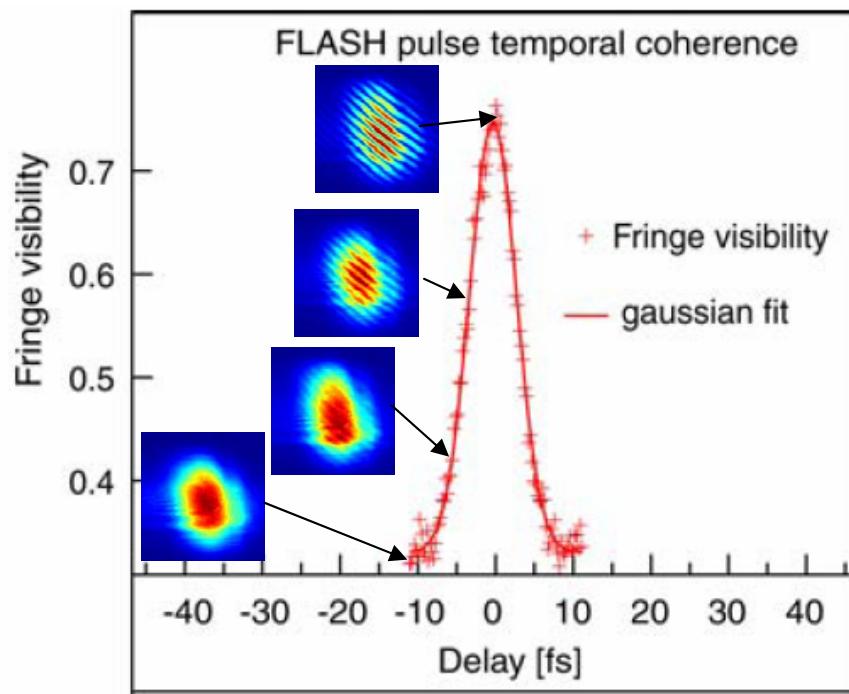
Uni Hamburg (A.Föhlisch, W.Wurth et al.)



- Delay Range:  $\pm 6$  ps
- Time resolution: < 1 fs
- Permanently installed in PG2

# Longitudinal coherence of FLASH pulses (2)

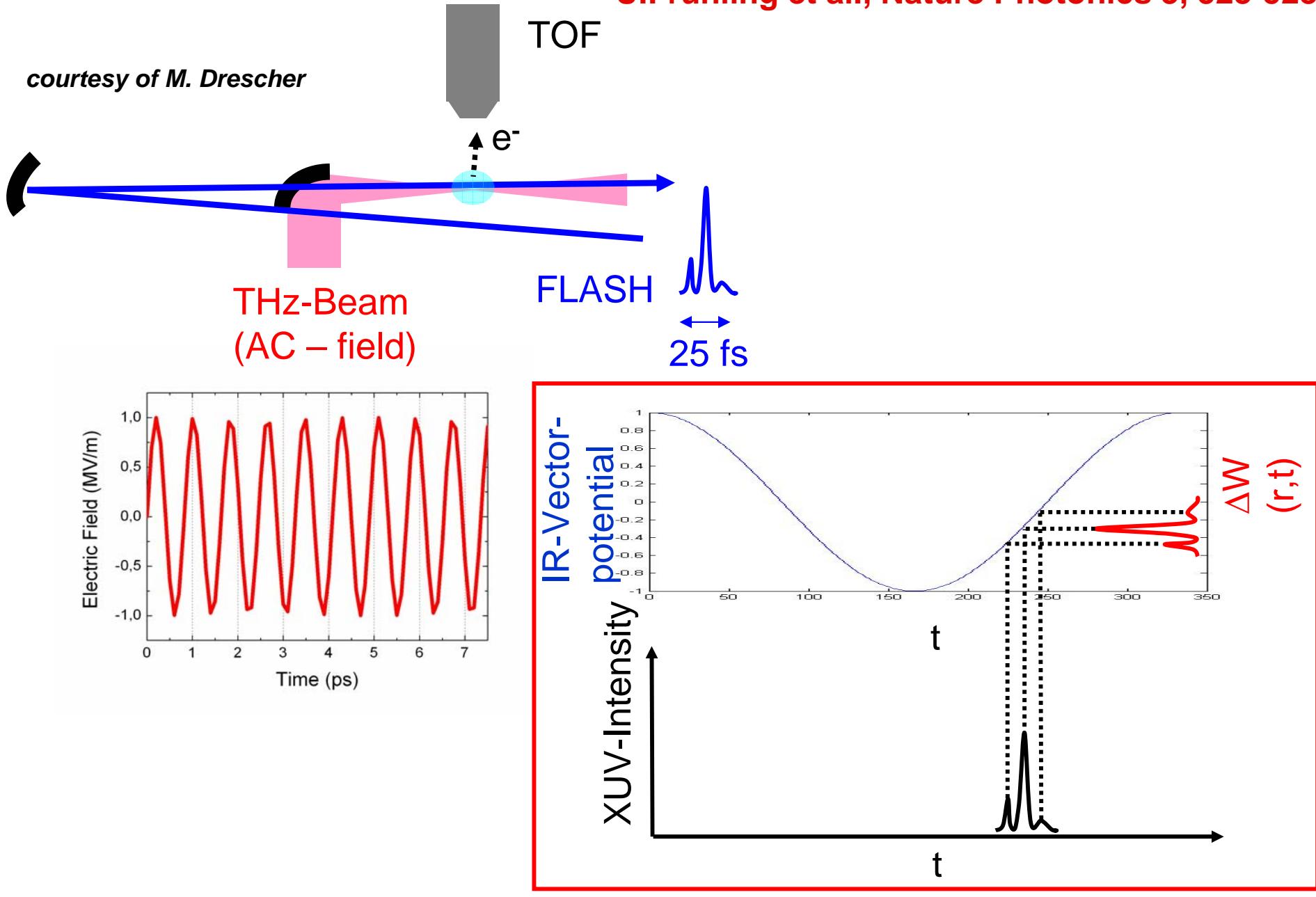
Interference fringes as a function of the temporal delay between the split and delayed X-ray pulses



# THz streak camera for timestructure of FLASH pulses

U. Frühling, M. Drescher et al.

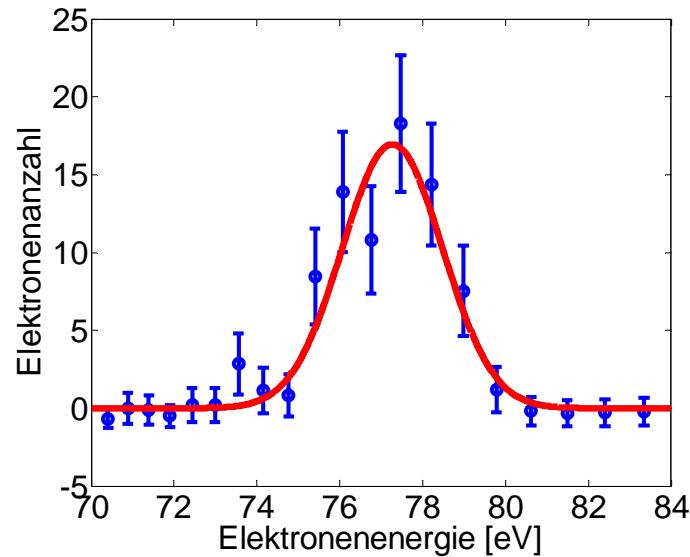
U. Frühling et al., Nature Photonics 3, 523-528 (2009)



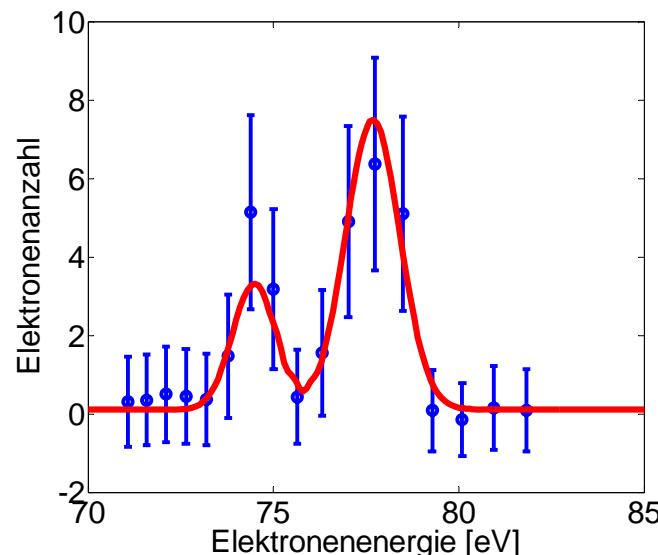
# Single shot spectra

U.Frühling et al., Nature Photonics 3, 523-528 (2009)

courtesy of U. Frühling



No evident sub structure:  
~ 90 % of the spectra

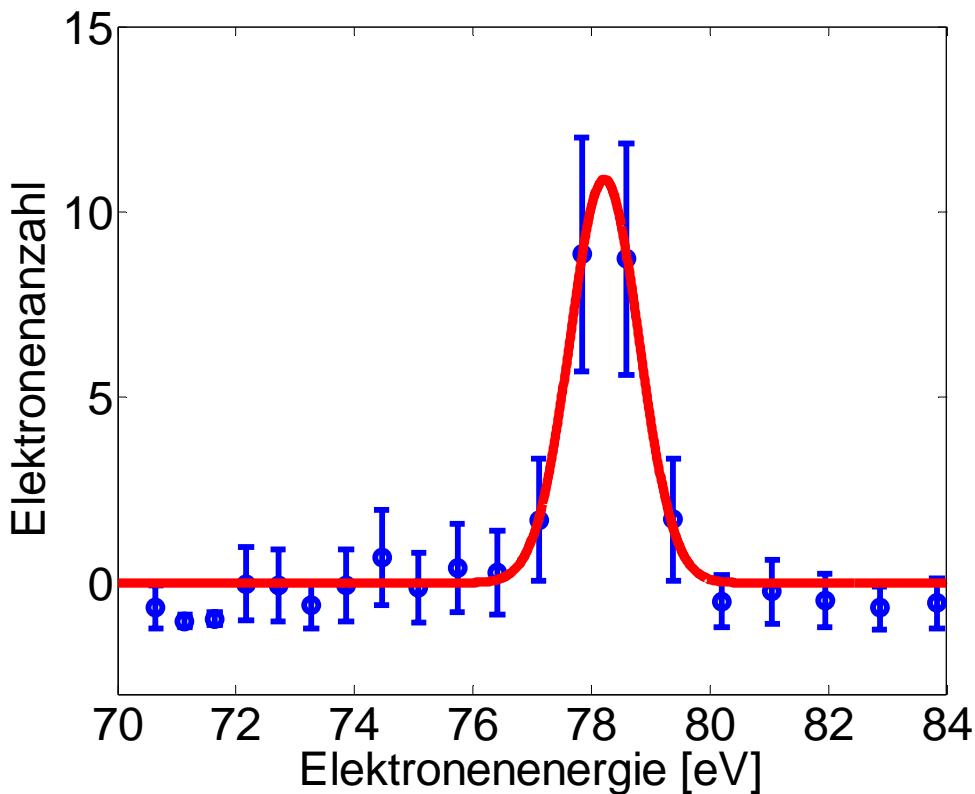


sub structure:  
~ 10 % of the spectra

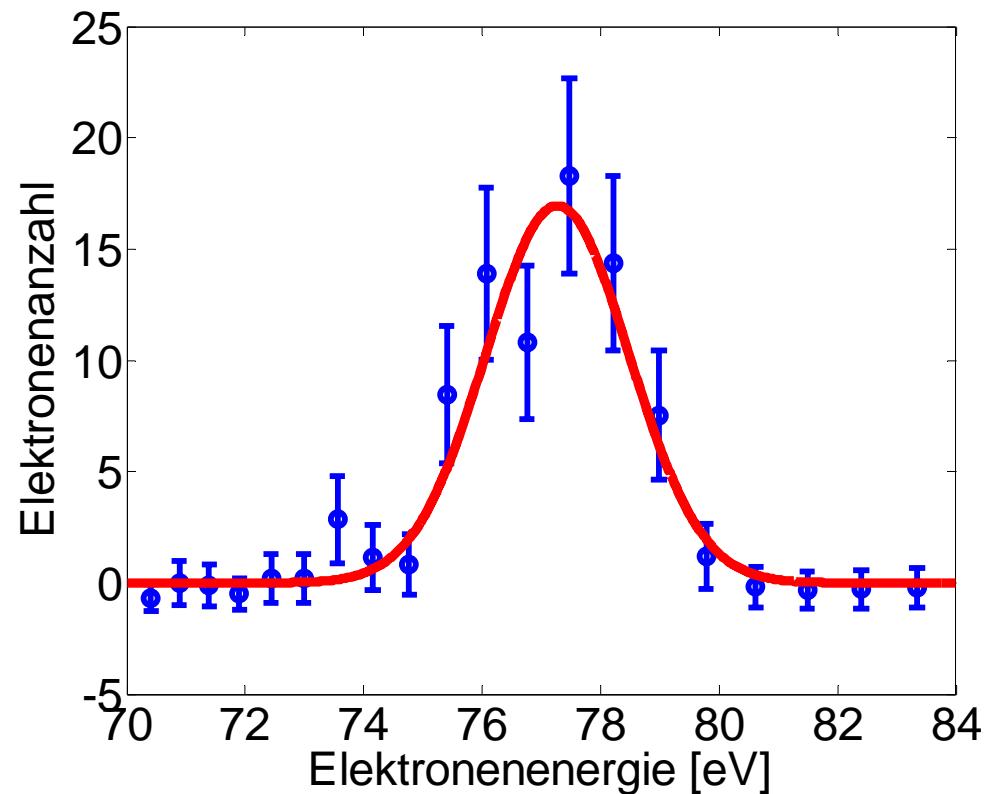
# Single shot spectra – one pulse

courtesy of U. Frühling

Perpendicular detector  
no streaking



parallel detector  
streaking



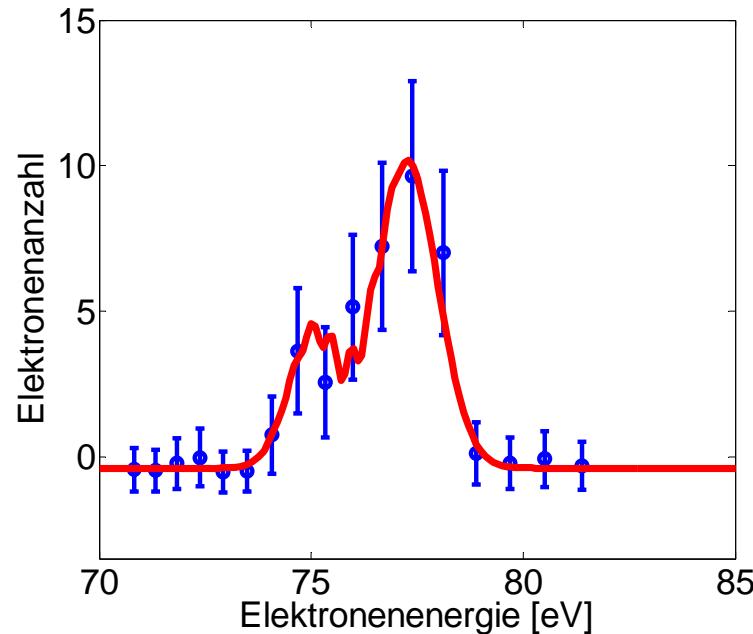
Pulse duration :  $(28 \pm 9)$  fs FWHM

FLASH: 13,5 nm  
Gas: Krypton (4p)



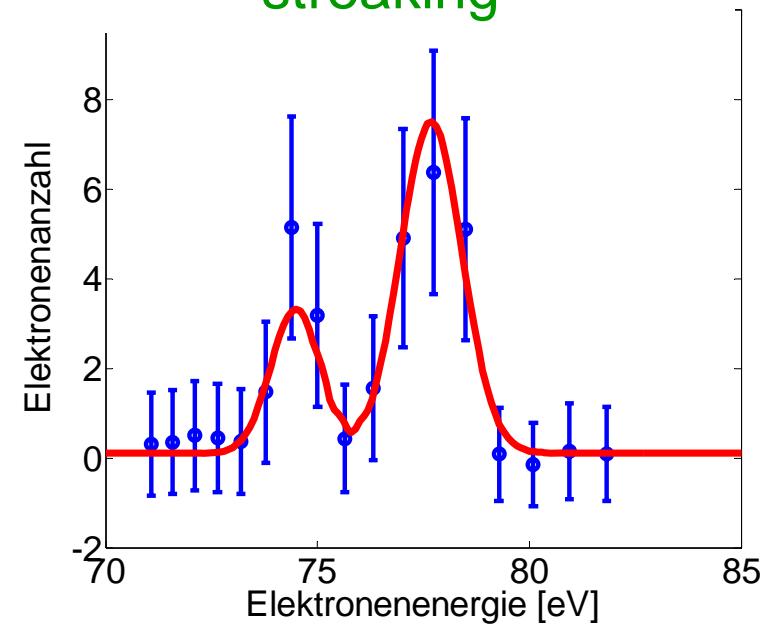
# Single shot spectra – double pulse

Perpendicular detector  
no streaking

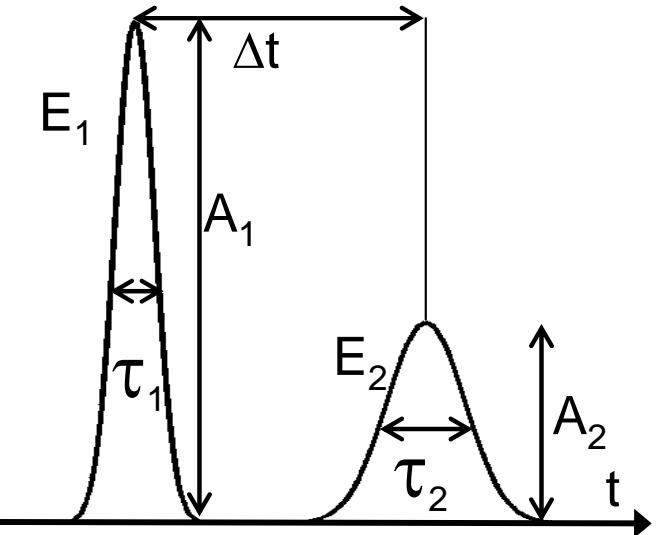


$$\Delta t = (9 \pm 4) \text{ fs}$$
$$(\tau_{\text{Subpuls}} \approx 1 \text{ fs})$$

parallel detector  
streaking



Fitparameter

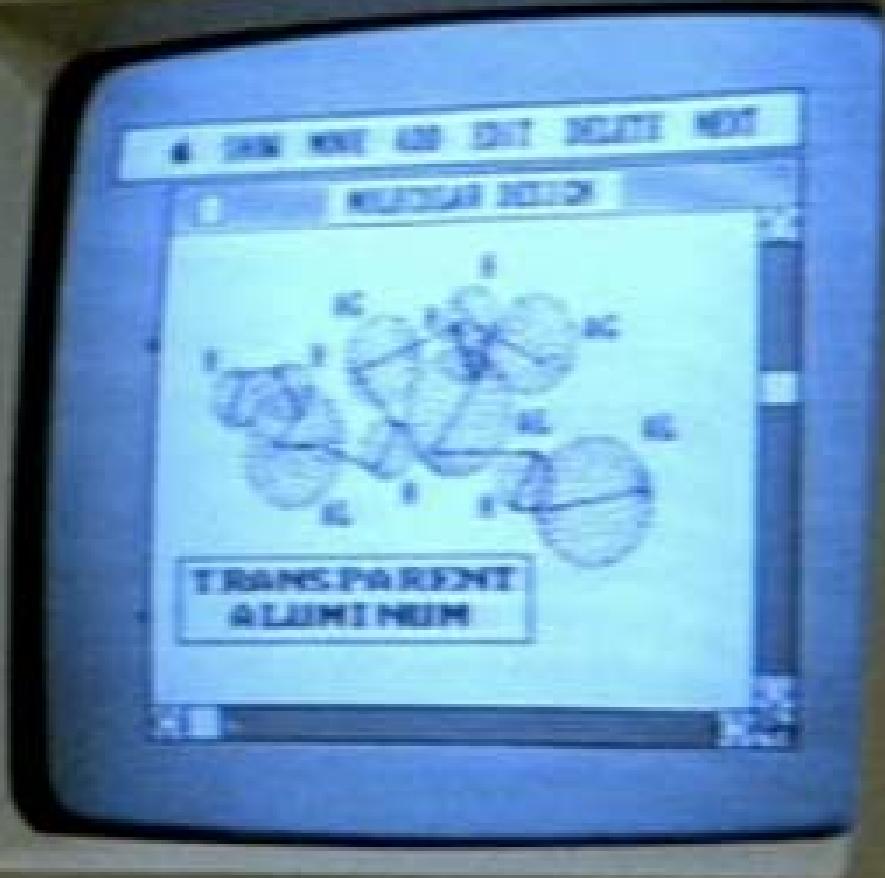


## FLASH Ultra-high intensity experiments

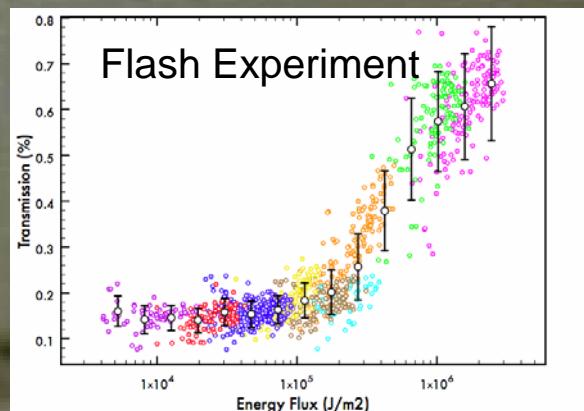
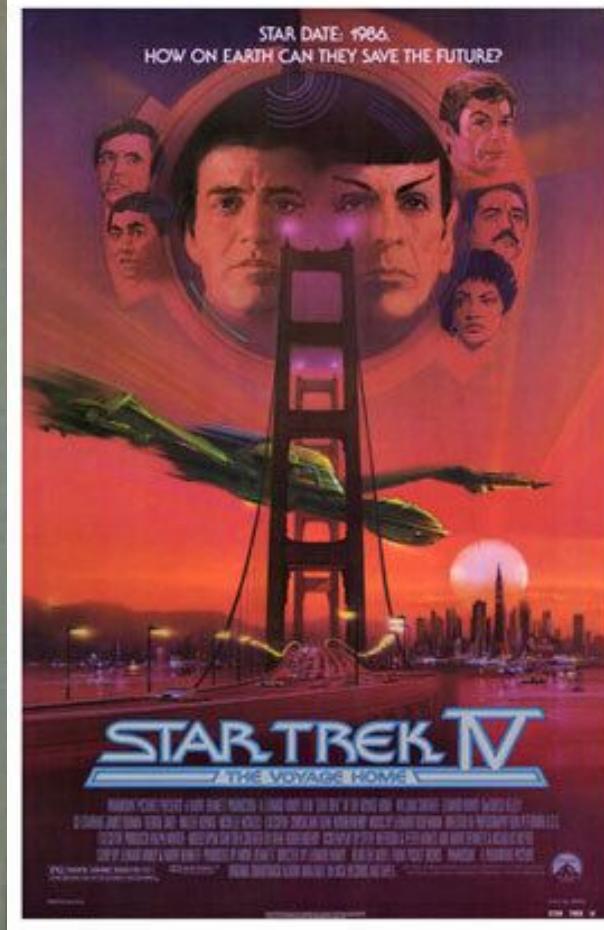


# Transparent Aluminium

(B.Nagler et al.)

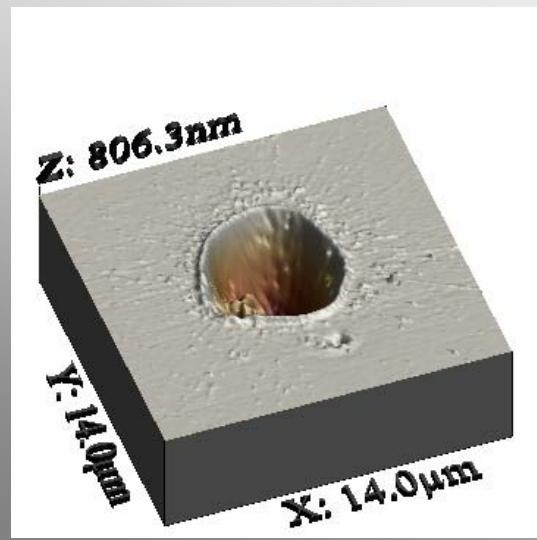
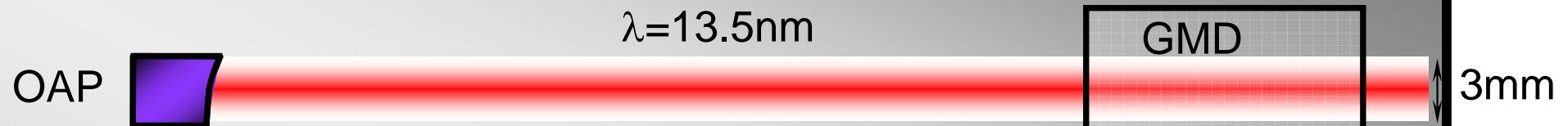


**FLASH**  
creates  
transparent  
aluminum



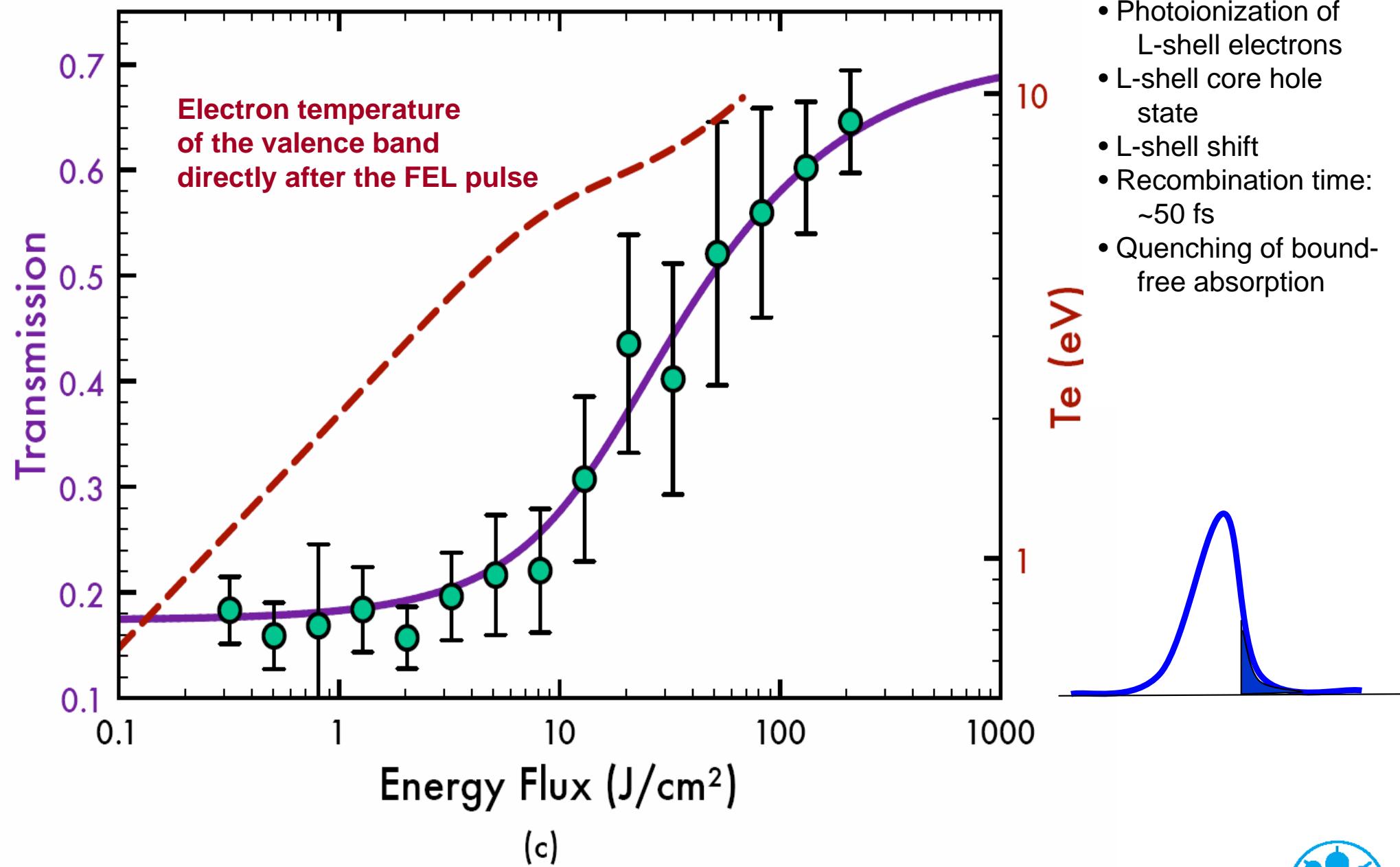
# Microfocusing setup

S. Bajt et al., Proc. of SPIE Vol. 7361, 73610J1-10 (2009)



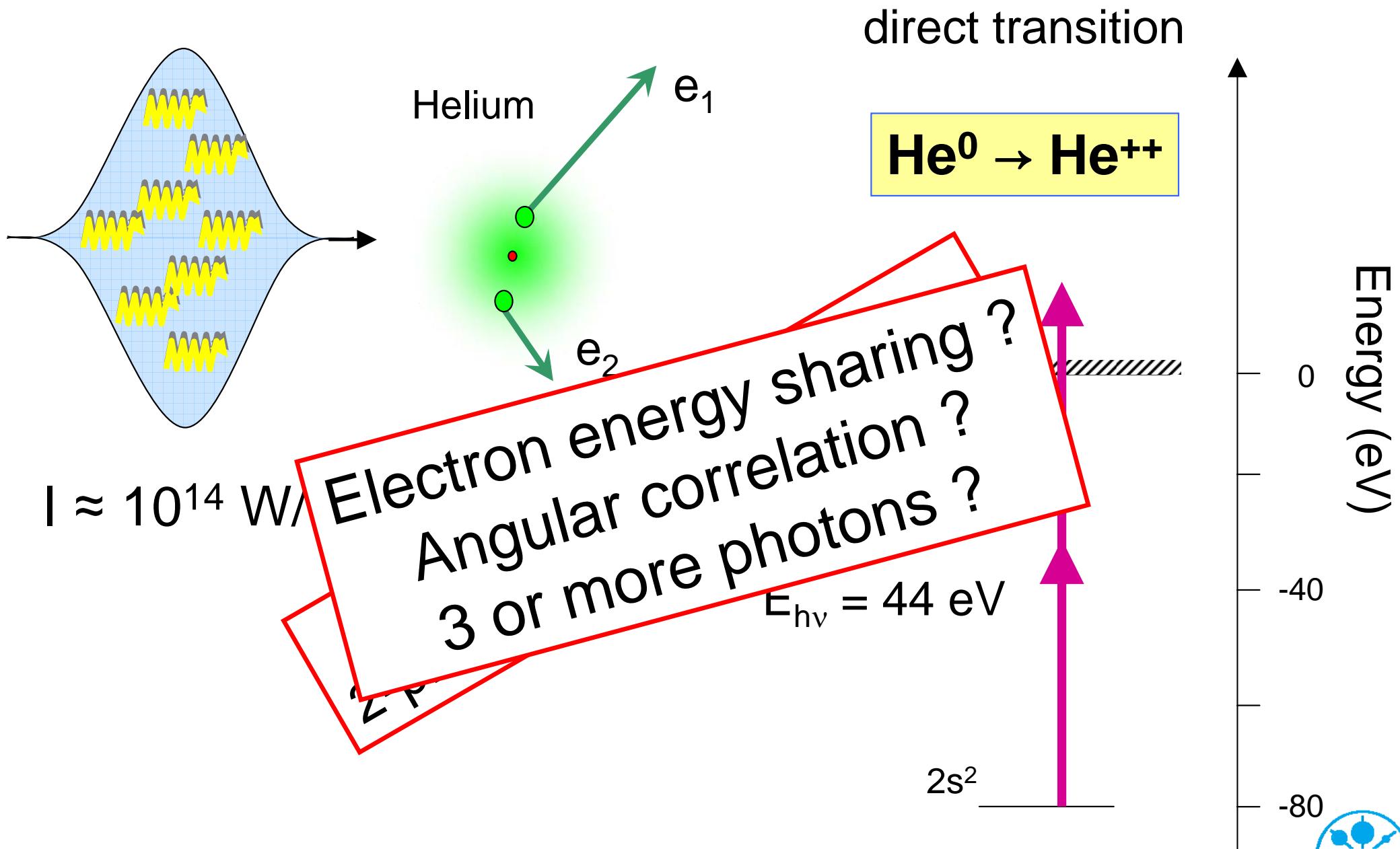
J. Chalupský et al., Opt. Express 15, 6036-6043 (2007)

# Transmission dependent on power density



# Two-Photon Double Ionization of He

(R.Moshammer, J.Ullrich et al.)



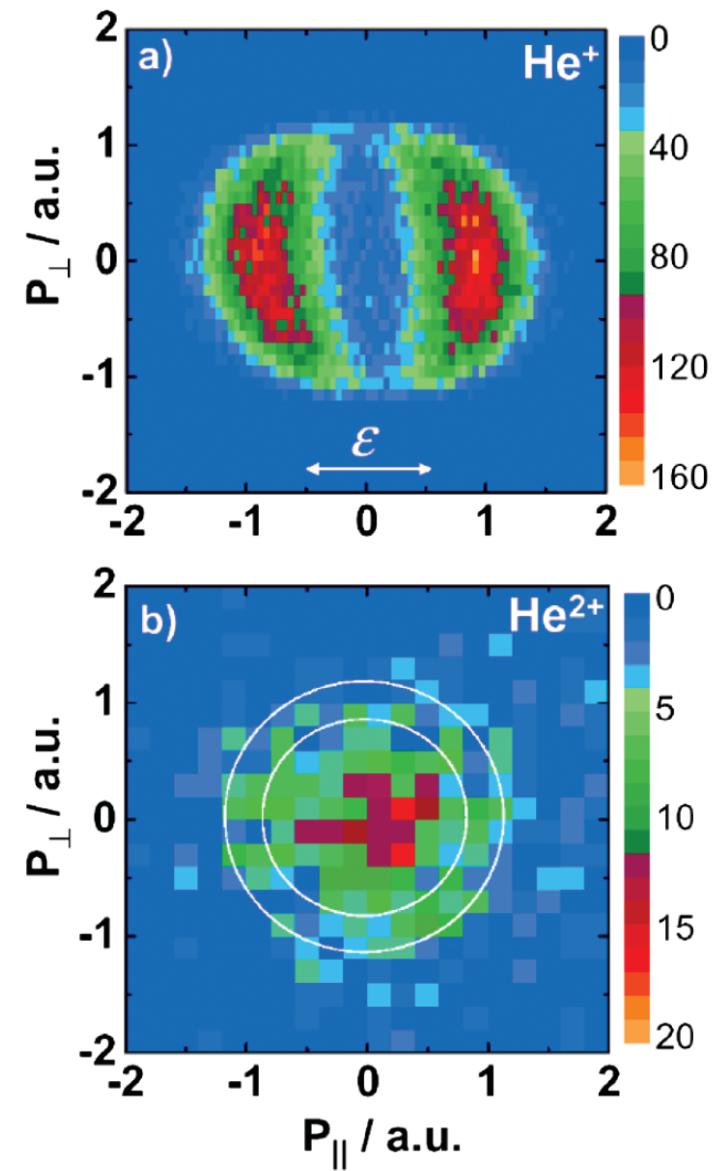
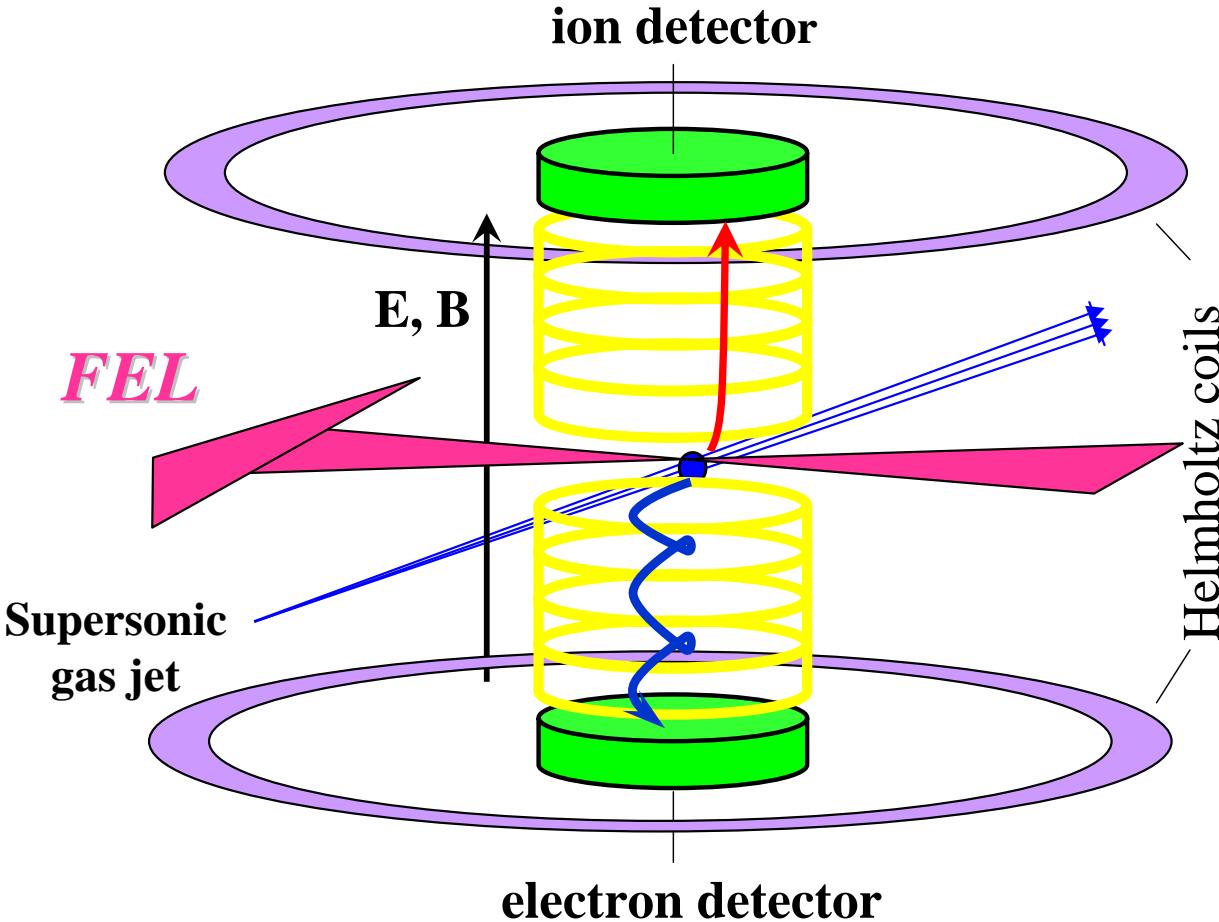
# Two-Photon Double Ionization of He: theory

## Theoretical papers (not complete)

- Palacios et al., PRA 77 (2008)  
Faist et al., PRA 77, 043420 (2008)  
Guan et al., PRA 77, 043421 (2008)  
Horner et al., PRA 77, 030703 (2008)  
Foumouo et al., NJP 10 (2008)  
Lambropoulos and Nikolopoulos ,NJP 10, 025012 (2008)  
Foumouo et al., JPB 41, 051001 (2008)  
Kheifets, JP 40 (2007)  
Ivanov and Kheifets, PRA 75, 024702 (2007)  
Nikolopoulos and Lambropoulos, JPB 40, 043407  
Kheifets et al., PRA 69, 043407  
Horner et al., PRA 69, 043407  
Parker et al., PRL 96, 143001 (2006)  
Foumouo et al., JPB 39, 427 (2006)  
Palacios et al., PRL 96, 143001 (2006)  
Kheifets and Ivanov, JPB 39, 1731 (2006)  
Barna et al., PRA 73, 023401 (2006)  
Nikolopoulos and Lambropoulos, JPB 39, 883 (2006)  
Madine et al., JPB 39, 4049 (2006)  
Cohen et al., JPB 39, 2693 (2006)  
Hu et al., JPB 38, L34 (2005)
- Themelis et al., JPB 37, 4281 (2005)  
de Castro et al., PRA 72, 023410 (2005)  
Lambropoulos et al., PRA 72, 013410 (2005)  
van der Hart and Bingham, JPB 38, 207 (2005)  
Barna, EPJ D33, 307 (2005)  
Bachau et al., PRA 71, 063405 (2005)  
Madine and van der Hart, JPB 38, 3963 (2005)  
Ishikawa and Midorikawa, PRA 72, 013497 (2005)  
van der Hart et al., JPB 38, L207 (2005)  
Mehring et al., JPB 38, 237 (2005)  
Nakajima and Tawara, PRA 70, 013412 (2004)  
Taylor et al., Phys. Scr. T105, 10, 154 (2004)  
Laulan and Bachau, JPB 37, 3521 (2004)  
Laulan and Bachau, PRA 69, 033408 (2004)  
Bachau, JPB 35, 509 (2004)  
Santra and Green, PRA 70, 0534001 (2004)  
McKenna and van der Hart, JPB 37, 457 (2004)  
Piraux et al., EPJ D26, 7 (2003)  
Taylor, Phys. Scr. T105, 31 (2003)  
Papadogiannis et al., PRL 90, 133902 (2003)  
Laulan and Bachau, PRA 68, 013409 (2003)  
Feng and van der Hart, JPB 36, L1 (2003)  
Papadogiannis et al., PRL 90, 133902 (2003)  
Nikolopoulos et al., PRL 90, 043003 (2003)  
Barna and Rost, EPJ D27, 287 (2003)  
Colgan and Pindzola, PRL 88, 173002 (2002)

Theory needs to be tested !!

# Approach: FLASH + Reaction Microscope

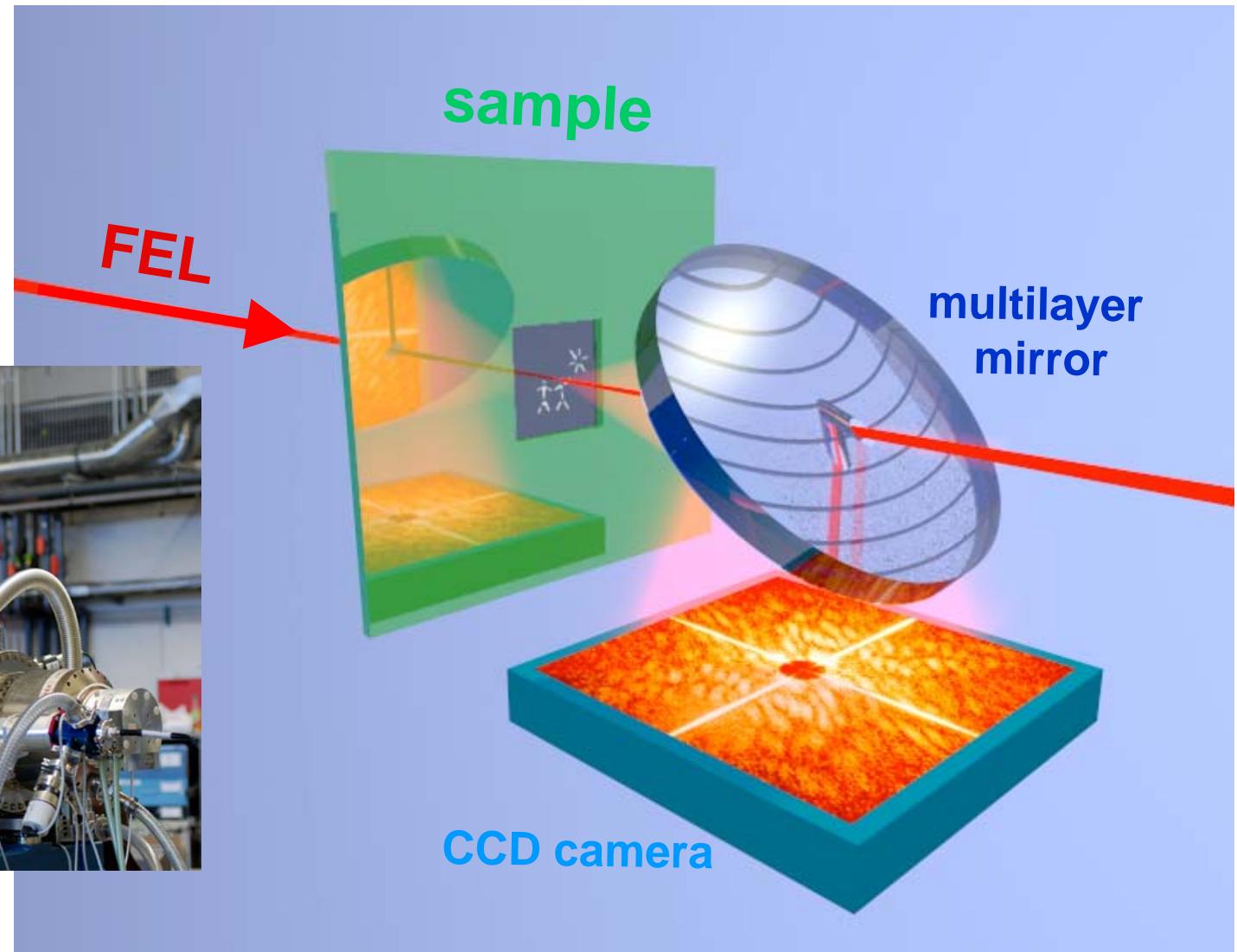


## FLASH imaging

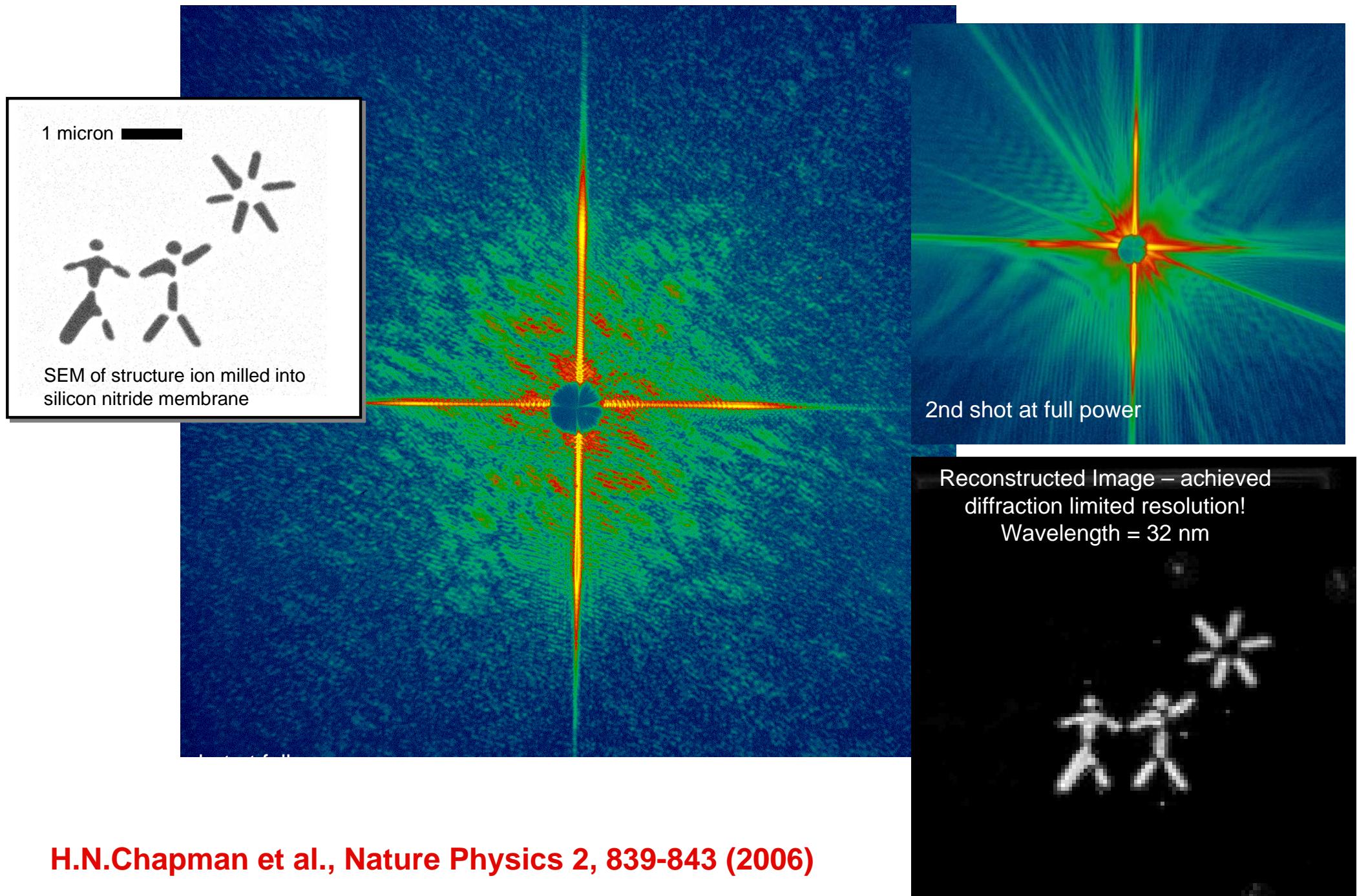


# Coherent single-shot X-ray diffraction imaging

(H. Chapman, J. Hajdu et al.)

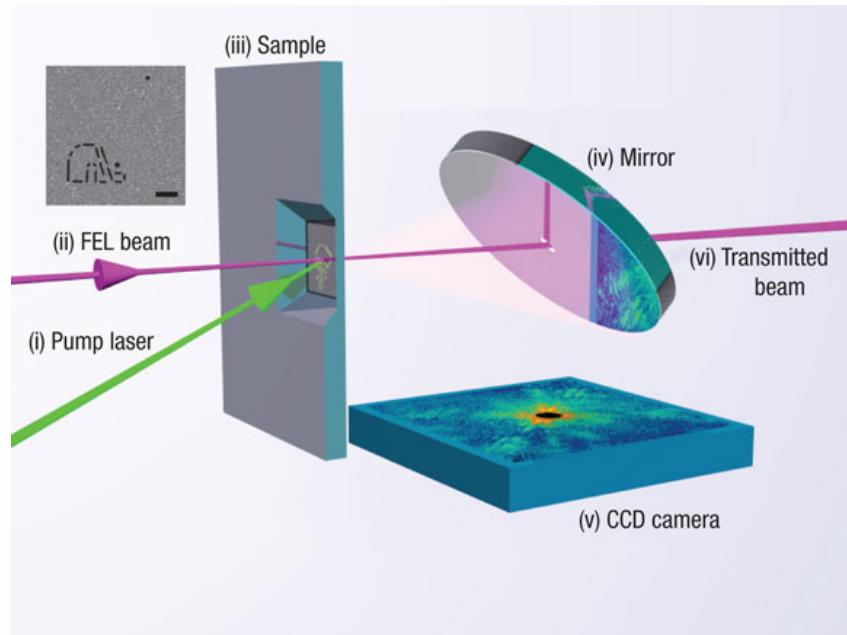


# Image reconstructed from ultrafast diffraction pattern

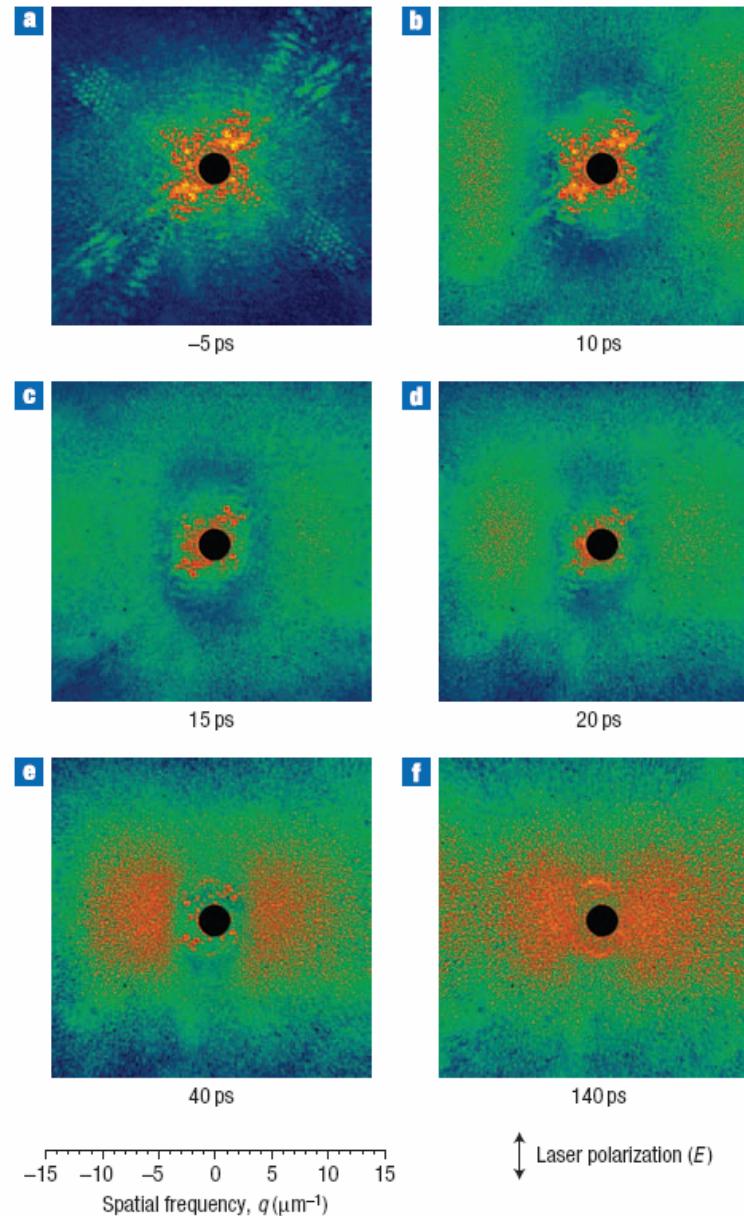


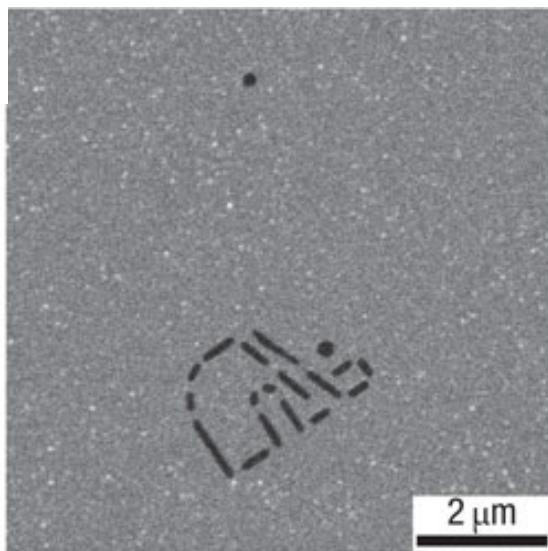
# Dynamic X-ray diffraction imaging (pump-probe)

## LETTERS

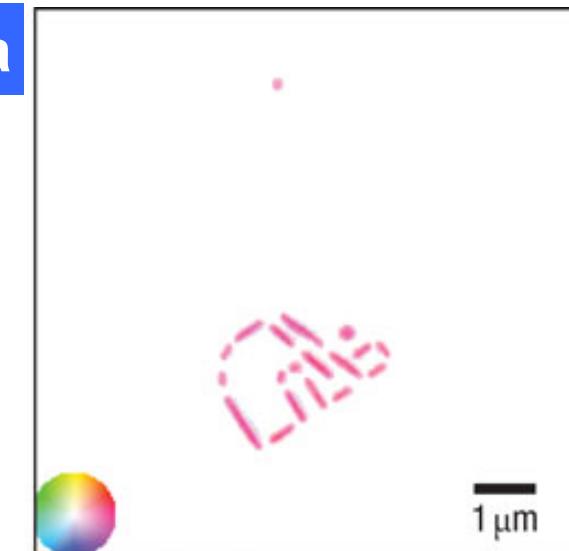


**Figure 1** X-ray dynamic diffraction imaging. A visible-light laser beam (i) incident from the left is focused onto the sample (iii) and acts as the excitation pulse. A 10-fs duration soft X-ray pulse at a wavelength of 13.5 nm from the FEL (ii) is focused to a 20- $\mu\text{m}$  spot in the same location as the visible-light laser at a continuously variable delay after the excitation pulse. The X-ray pulse diffracts from the sample, carrying information about the transient sample structure to the CCD detector (v) in the form of a coherent diffraction pattern. A 45° mirror (iv) is used to separate the direct beam from the diffracted light: the direct FEL beam (vi) passes straight through a hole in the mirror and is not detected in the CCD image. A 100-nm-thick zirconium filter over the CCD chip makes the detector blind to the laser excitation pulse. The sample (iii) consisted of a nanometre-resolution pattern etched into a silicon nitride membrane using a focused ion beam (FIB), providing a well-defined control sample so that the time evolution of a known structure could be observed. The path length from sample to CCD is 53 mm and the detected numerical aperture is 0.25, giving a spatial resolution of 27 nm in the sample plane.





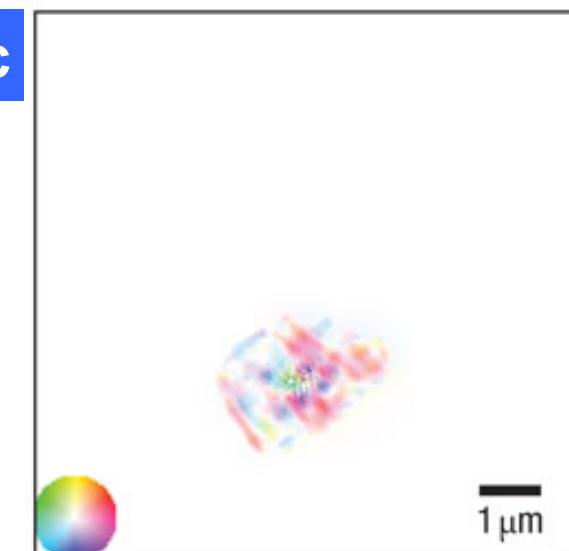
SEM image



$-5\text{ ps}$



$10\text{ ps}$



$15\text{ ps}$

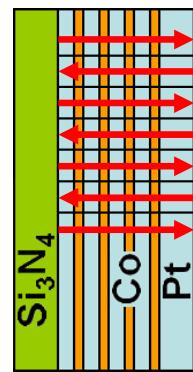
## imaging using harmonics



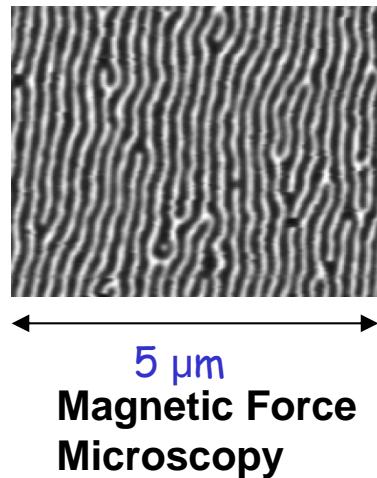
# Magnetic scattering of Co/Pt 5th harm. - 1.6 nm

DESY, BESSY, Univ. Heidelberg, Rhein-Ahr-Campus Remagen

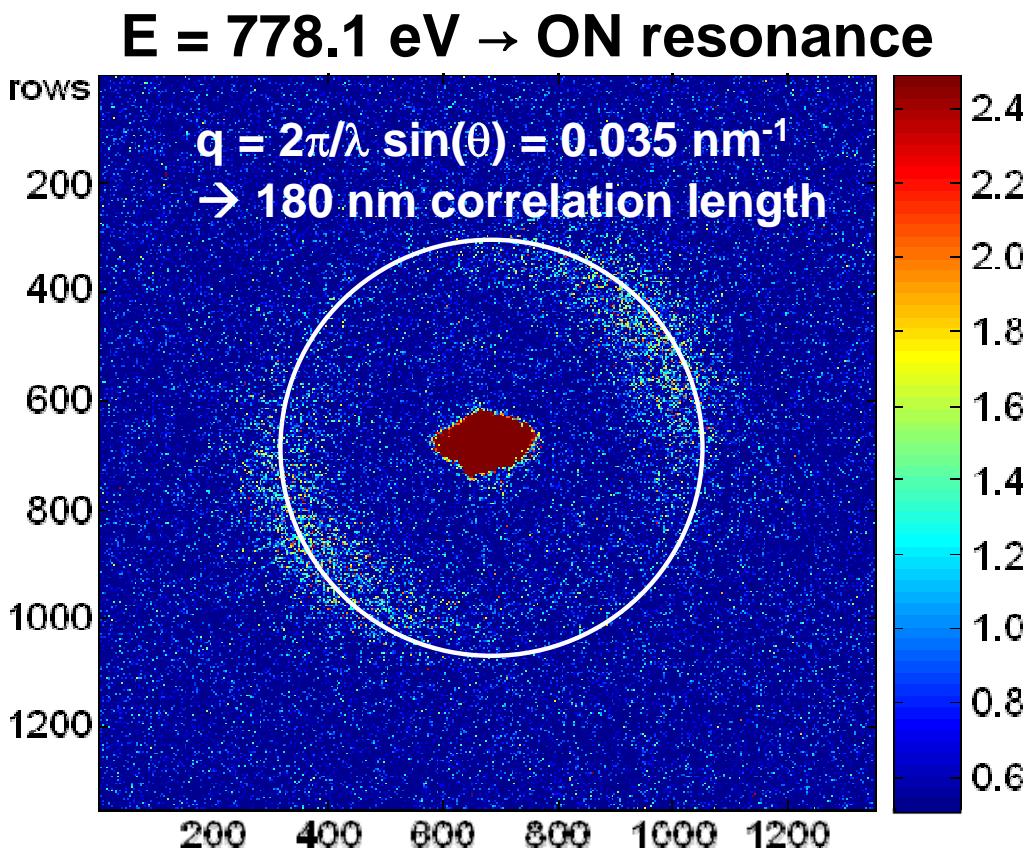
Proof-of-principle using 5th harmonic at 1.59 nm (Co L<sub>3</sub>)



M



Co/Pt multilayers form a periodic magnetic domain pattern with magnetic moments  $m_j$  parallel and antiparallel to the surface normal



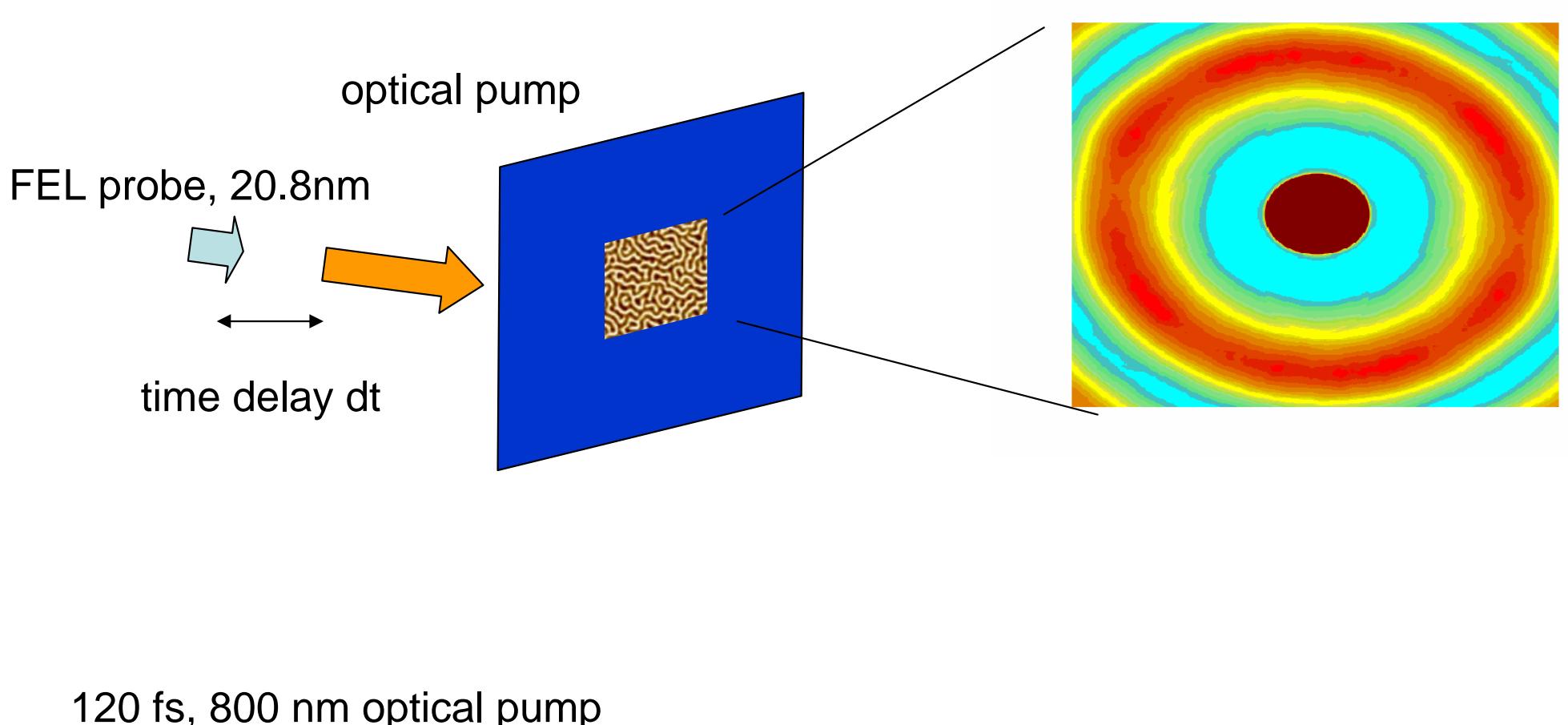
**study fs-dynamics**

**magnetism**



# Time resolved magnetic scattering

courtesy of C. Gutt

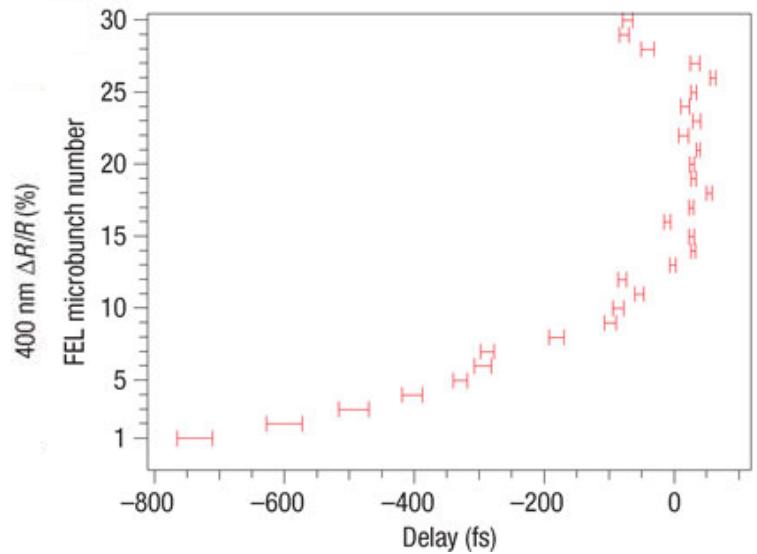
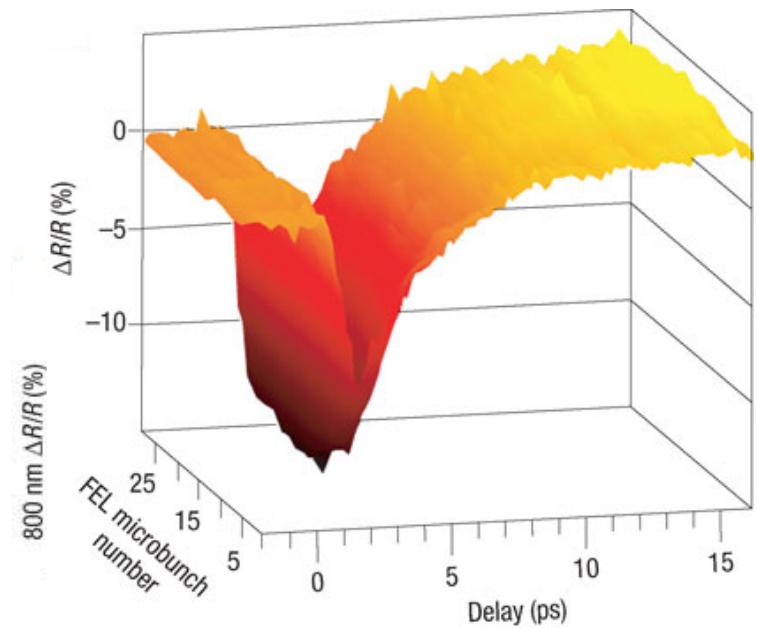
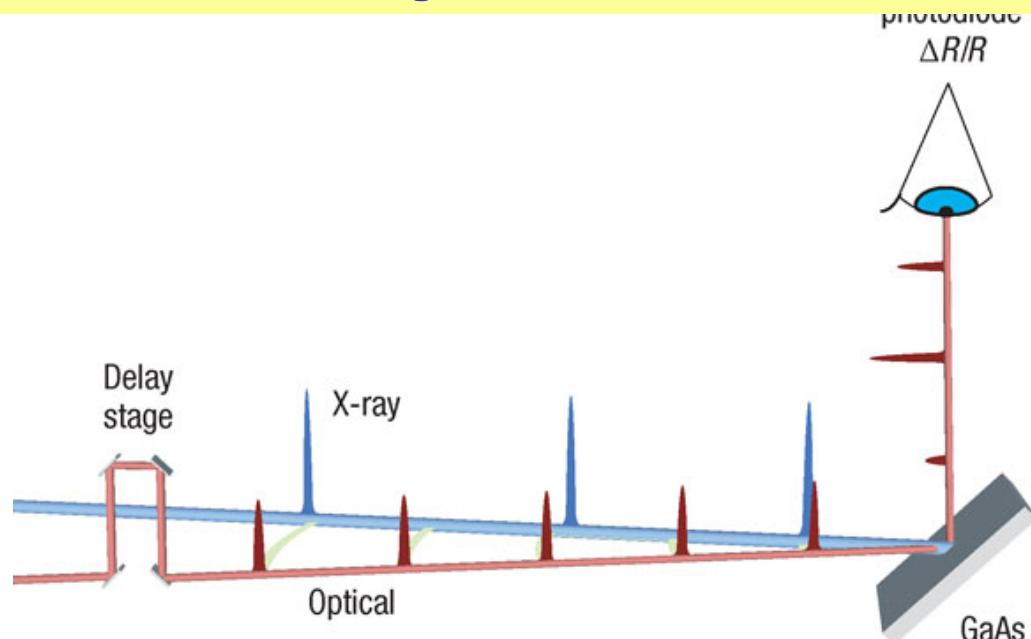


**study fs-dynamics  
electronic properties of solids**



# Femtosecond X-ray/optical reflectivity studies (FU Berlin, Uni HH, DESY)

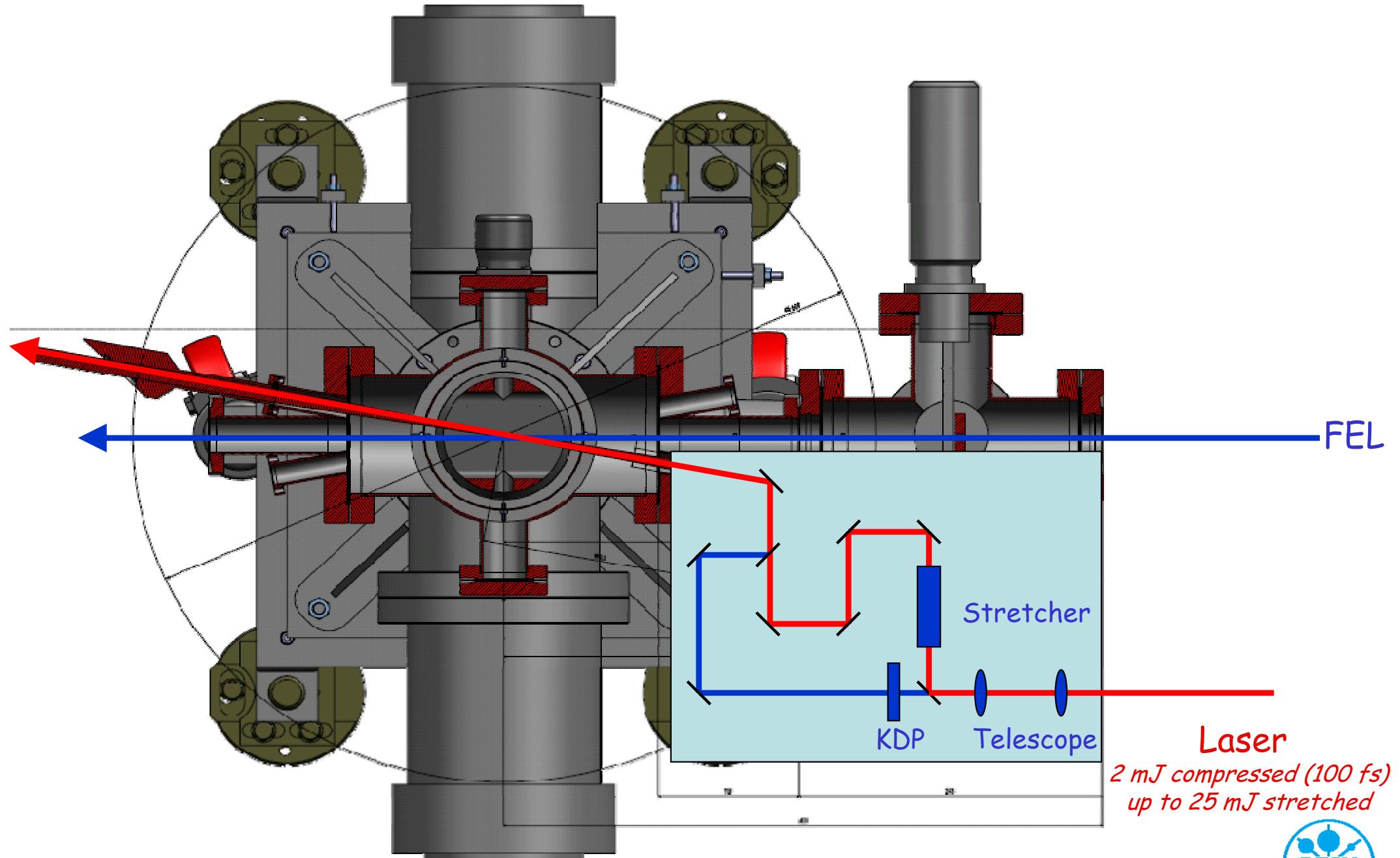
- investigate GaAs crystal
- change optical properties with FEL pulse
  - learn about electronic properties
- use reflectivity change as arrival time monitor
  - Intrabunch timing drift



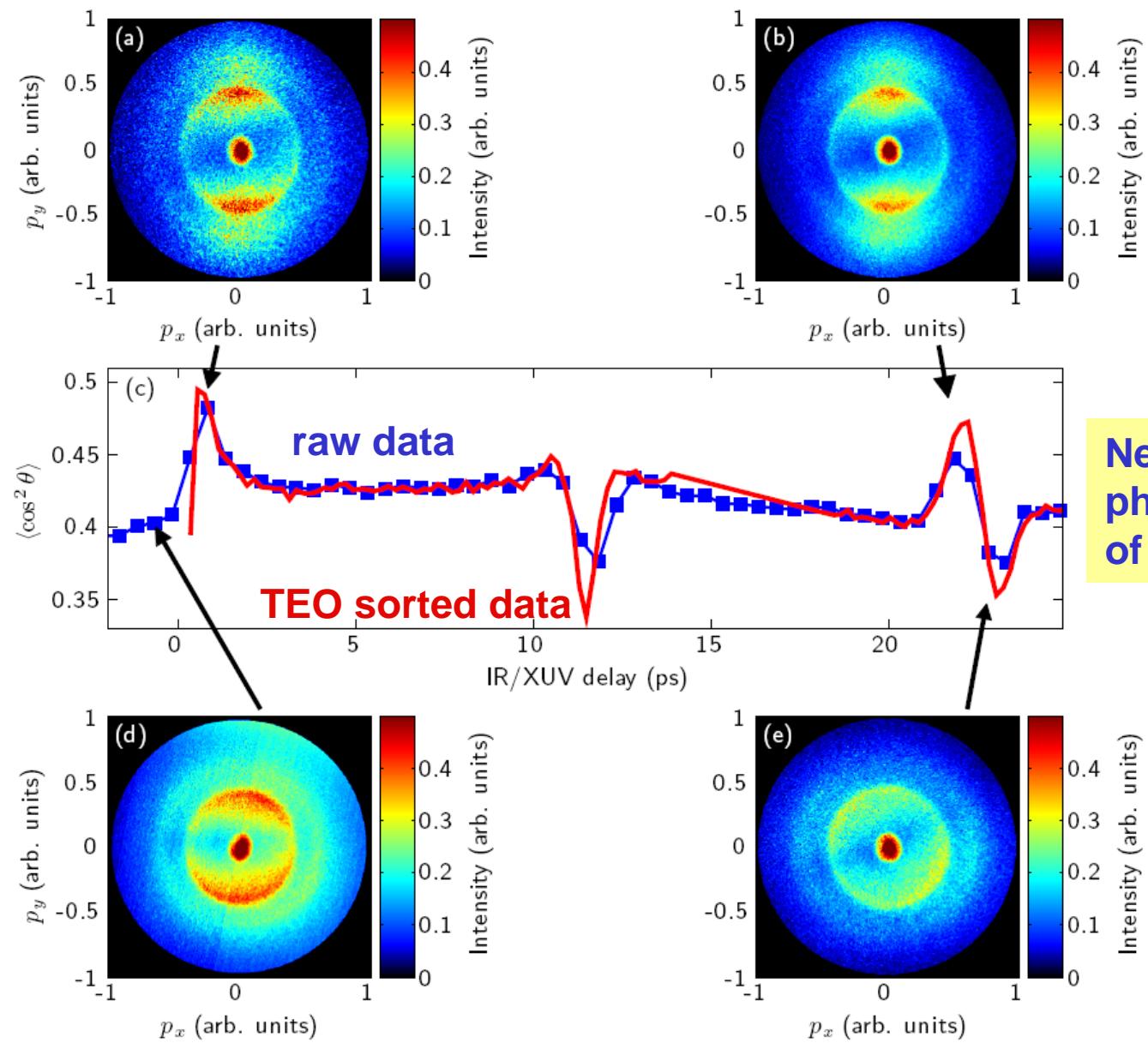
**study fs-dynamics  
molecules**



# AMOLF VMIS: Pump probe setup



# Impulsive alignment of molecules



**Still not even half the groups  
have been presented so far ...**



# Summary: Publications

**68 photon science publications since 2006:**

e.g.:

- 1 Nature
- 2 Nature Physics
- 5 Nature Photonics
- 14 Phys. Rev. Lett.
- 9 Phys. Rev. A,B,E
- 7 Appl. Phys. Lett.
- 6 J. Phys. B
- 1 Optics Lett.
- 4 Optics Express

in addition, more than 10 submitted

... and not to forget the ~ 50 papers/year  
on the technical subtleties of this fascinating light machine!

[http://hasylab.desy.de/facilities/flash/publications/selected\\_publications/](http://hasylab.desy.de/facilities/flash/publications/selected_publications/)



# Thanks.

